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ELECTRONIC PROGRESS

RAYTHEON

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ARSR-2

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ELECTRONIC PROGRESS

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RAYTHEON

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COVER

THE COVER

Raytheon's new air route surveillance radar offers to air traffic controllers an effective tool for handling jet-age problems. The ARSR-2 is the subject of this issue's feature article.

ARSR-2

As air traffic continues to grow in density, complexity, and speed, the Federal Aviation Agency is tightening up its traffic control system as fast as funding and the state of the electronic art will allow. To supplement the 32 Raytheon ARSR-1A systems now in use throughout the country, the FAA has recently ordered from Raytheon 18 ARSR-2 systems, which incorporate several significant advances over previous air route surveillance radars.

The ARSR's are used primarily for enroute surveillance of airplanes, since other FAA radars, known as ASR's (airport surveillance radars) are responsible for monitoring aircraft approaching or leaving an airport.

The first ARSR-2 will be installed in the summer of 1961. When all 18 are added to the existing ARSR-1A's, the tightened network will provide practically continuous radar surveillance along the nation's major airways (see Figure 1). Each ARSR-2 system will provide a range of almost 200 nautical miles on a small jet airplane, such as a T-33, and will cover an area of over 150,000 square statute miles.

The ARSR-2 is a modification of the ARSR-1A, which was the first production radar to exploit the high-power capabilities of the Raytheon Amplitron tube. The significant advances offered by the ARSR-2 are the addition of a parametric RF preamplifier for longer range, a new [illegible] coverage antenna for improved [illegible] ratio, and a new

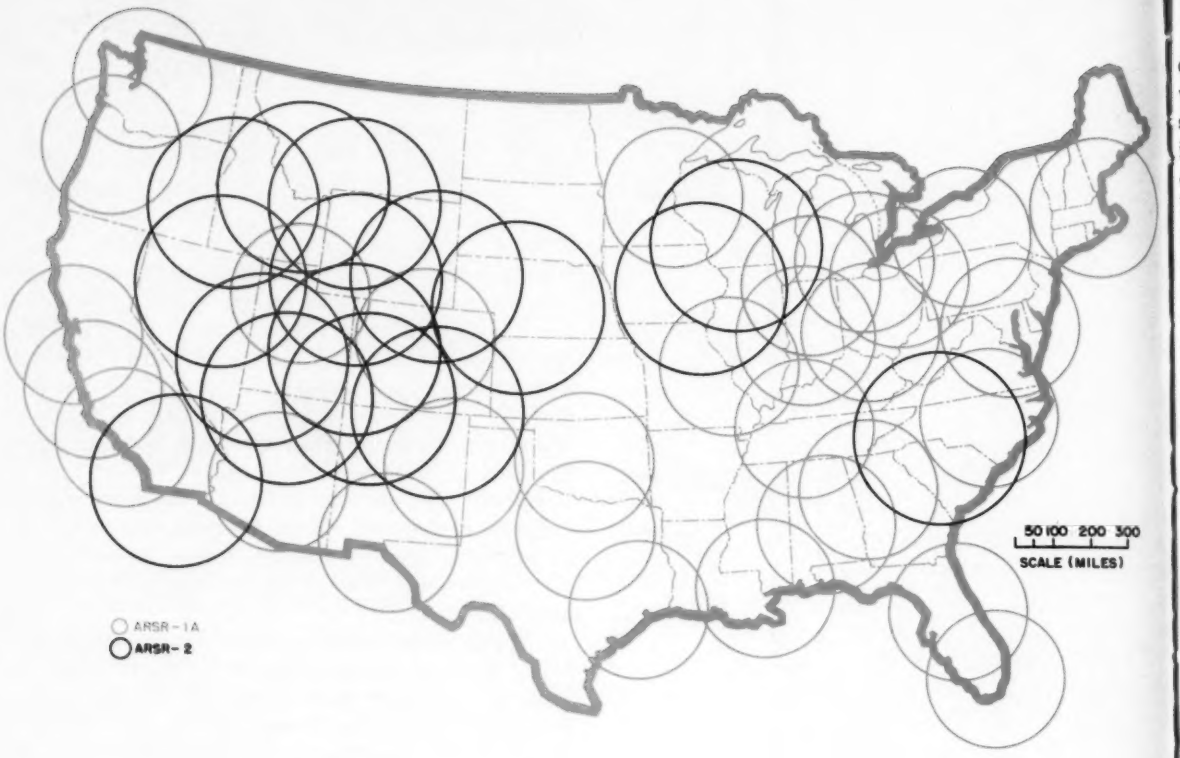


Figure 1. This map shows the location of 32 ARSR-1A systems and 16 ARSR-2 systems. In addition to these systems, the Navy is utilizing two ARSR-1A's for missile range surveillance, and the FAA is planning to install ARSR-2's in Hawaii and Guam. There are also two ARSR-1A's located in Switzerland

staggered repetition period MTI (moving target indicator) for eliminating moving target blind speeds.

General Description

The ARSR-2 is a 5-megawatt, dual-channel, L-band system. All major units of the system except the antenna are duplicated to provide the reliability essential for continuous operation. Provisions also are incorporated to enable complete maintenance and testing of the standby channel while the operating channel is in use. An automatic performance monitor is built into the system to signal the operator if performance falls below preset limits. If a malfunction should occur in the operating channel, the operator at the master console can select the standby channel and have it "on the air" in less than 15 seconds. The FAA reports that operational availability of the ARSR-1A equipments is 99.5 per cent. It is anticipated that the reliability of the ARSR-2 will be at least as good.

A major problem which arises as the performance of radar systems is increased is the detection of undesired targets. A radar system designed to detect a T-33 at a range of almost 200 nautical miles will also detect many targets of no interest to the controller. The operator utilizes a PPI (plan position indicator) to keep track of aircraft. Targets other than aircraft which appear on the PPI only detract from the usefulness of the radar system. The problem of unwanted targets becomes more severe as the range performance of a radar system is increased. Examples of unwanted targets are signals reflected from the ground, rain, birds, and insects, as well as interference from nearby radars. The ARSR-2, for example, will detect seagulls out to 45 nautical miles.

WILLIAM W. SHRADER *is a Staff Engineer in the Systems Section of the Surface Radar and Navigation Operations, Equipment Division. Prior to joining Raytheon in 1956, he was a group leader in the Physical Research Unit of the Boeing Airplane Company in Seattle, where he analyzed and determined criteria for bomber defense systems. At Raytheon, he was previously a systems engineer on the ARSR-1 radar system and project engineer on the Amplitron Kit for the ARSR-1A. Mr. Shrader received his B.S. degree in Electrical Engineering from the University of Massachusetts and has done post-graduate work at the University of Washington and Northeastern University.*

A major portion of a high-performance radar is devoted entirely to the problem of eliminating unwanted signals from the display while retaining desired targets. The new antenna used on the ARSR-2 is an example of a radar system improvement incorporated specifically to cope with this problem. The MTI system attenuates signals reflected from stationary objects but permits moving targets to be displayed. The video integrator is used to enhance weak signals and to attenuate interference from other radar systems. Finally, the circular polarizer is provided to attenuate signals reflected from rain.

The sequence of PPI photographs in Figure 2 shows how some of the various clutter reducing techniques employed permit the use of the ARSR-2 under weather and ground-clutter conditions that would otherwise seriously impair the usefulness of a radar system. These pictures were taken on an ARSR-1A, during a severe thunderstorm. Since the camera shutter was left open for three revolutions of the radar antenna for each picture, desired aircraft targets appear as three closely spaced dots. The sequence was taken over a twenty-minute period so that the aircraft targets moved considerably between pictures. The PPI radius represents 40 nautical miles.

The first picture (Figure 2a) shows normal radar video with linear polarization. Most of the desired airplane targets are obscured by signals reflected from the storm.

The second picture (Figure 2b) shows the effect of circular polarization. The signal intensity from the storm is greatly attenuated, but signals reflected by ground clutter, such as the mountains shown in the picture at 11 o'clock, 12 o'clock, and 4 o'clock, are essentially unaffected.

The third picture (Figure 2c) shows the use of the MTI receiver and circular polarization. Note that the mountains which showed in the second picture are now eliminated. In addition, all the ground clutter near the center of the picture is now eliminated, although some signal return from the storm is still evident.

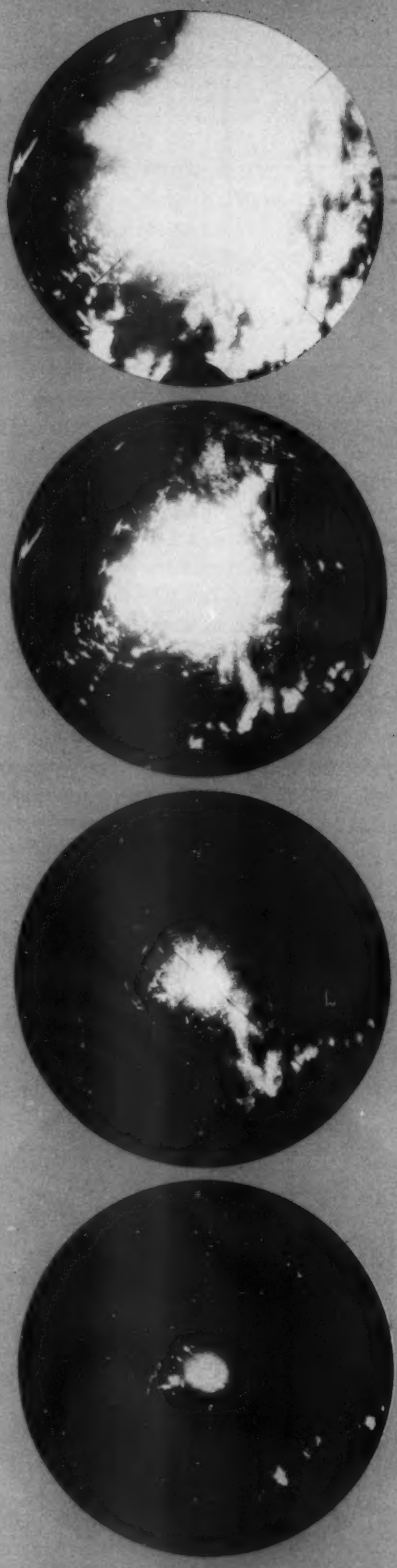
The fourth picture (Figure 2d) shows the addition of STC (sensitivity time control) to the operating conditions of Figure 2c. Aircraft targets are now visible over almost the entire display.

MTI System

The MTI system of the ARSR-2 incorporates a two-delay-line feedback canceller with pulse-to-pulse staggered repetition periods. The purpose of the MTI system is to filter out stationary targets while allowing moving targets to be displayed on the PPI.[1] With an

[1] (An excellent discussion of MTI systems appeared in "An Introduction to MTI System Design" by T. A. Weil in the May-June 1960 issue of ELECTRONIC PROGRESS.)

Figure 2.



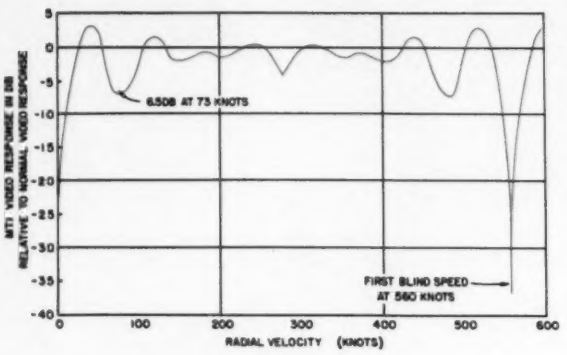

MTI VIDEO RESPONSE IN DB RELATIVE TO NORMAL VIDEO RESPONSE
6.5DB AT 73 KNOTS
FIRST BLIND SPEED AT 560 KNOTS
RADIAL VELOCITY (KNOTS)

Figure 3.

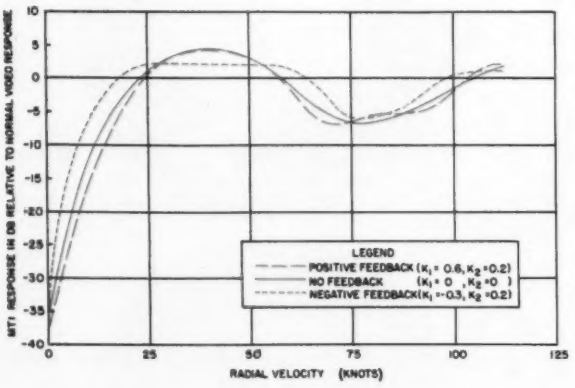

MTI RESPONSE IN DB RELATIVE TO NORMAL VIDEO RESPONSE
LEGEND
POSITIVE FEEDBACK (K_1 = 0.6, K_2 = 0.2)
NO FEEDBACK (K_1 = 0, K_2 = 0)
NEGATIVE FEEDBACK (K_1 = -0.3, K_2 = 0.2)
RADIAL VELOCITY (KNOTS)

Figure 4.

airplane flying over a mountain, the ARSR-2 MTI system rejects the signal from the mountain but allows the airplane signal to be displayed if the airplane signal is at least 1/500 as strong as the mountain signal. This capability of the MTI is known as SCV (subclutter visibility). The ARSR-2 has an SCV of 27db. Because the SCV is finite, it is desired to have as high as possible a ratio of target signal to ground-clutter signal.

The response of an MTI system to a moving target depends on the component of the target's velocity towards or away from the radar antenna. If the target is moving tangentially, it will not be displayed. If the target moves a multiple of one-half wavelength of the transmitted frequency nearer or farther from the radar system between pulses, it will not be seen by a fixed-repetition-period MTI. The radial target velocities corresponding to a movement of one-half wavelength between pulse are known as "blind speeds." Blind speeds for the ARSR-1A radar system occur at 80, 160, 240, . . . knots. By varying the interval between consecutive radar pulses, the number of blind speeds can be considerably reduced. The ARSR-2 utilizes three different pulse intervals in the ratio of 6 to 7 to 8. Blind speeds occur at 560 knots and multiples thereof. The velocity response curve of the MTI system of the ARSR-2 is shown in Figure 3.

The feedback incorporated in the dual canceller permits adjusting the MTI response to slow-moving targets, and scan-modulated clutter. Figure 4 shows how varying the feedback affects the low-velocity response of the MTI system. The feedback is adjustable from the master console, and the operator can use it to optimize system response depending on the wind and antenna speed.

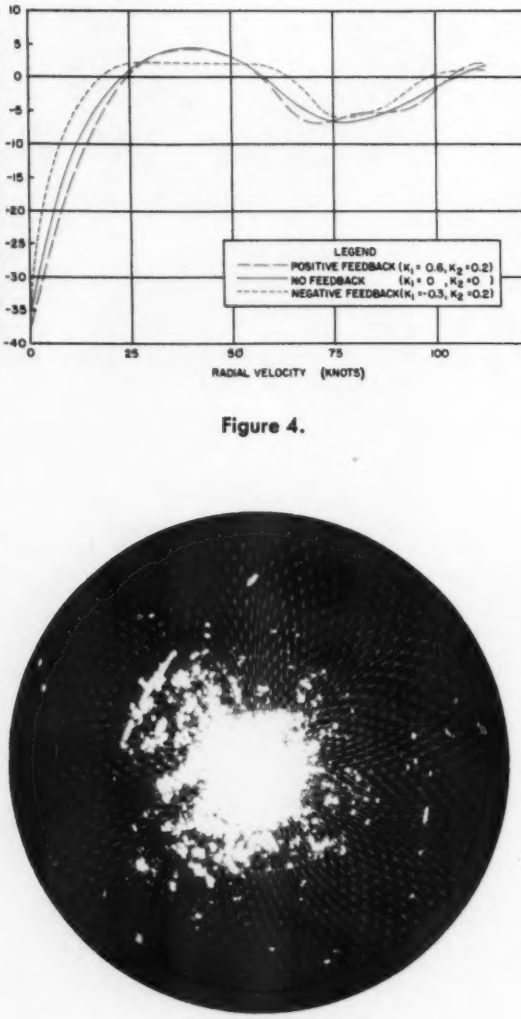


Figure 5.

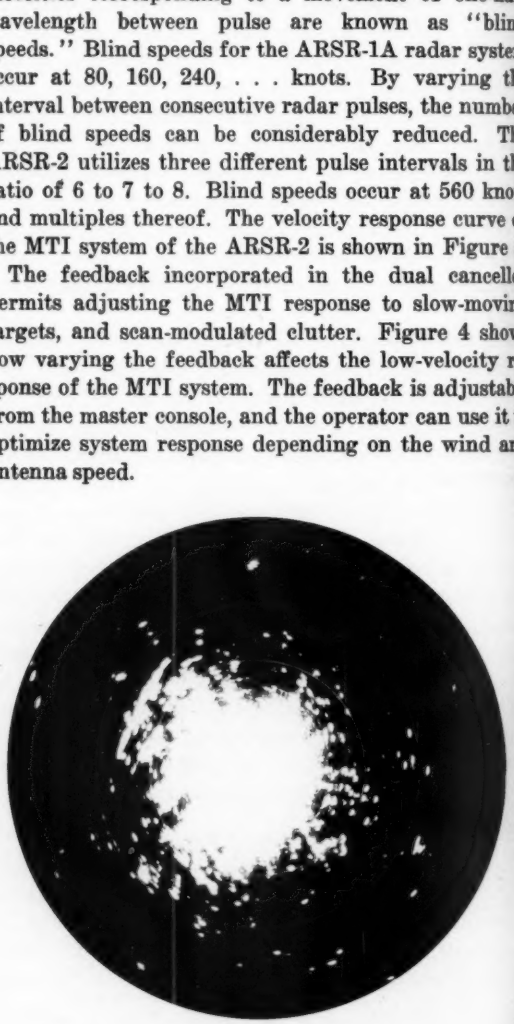


Figure 6.

Video Integrator

The ARSR-2 incorporates a delay-line video integrator for integrating normal video. The main advantages of the video integrator are the elimination of random pulse interference and an enhancement of weak target signals. The video integrator does not render detectable targets that would otherwise not be detected, but it does improve the peak-signal to rms-noise ratio, making it easier for the operator to distinguish between noise and targets on the PPI. Figure 5 shows normal video with a larger amount of random pulse interference. Figure 6 taken immediately after Figure 5, shows the use of the video integrator. The random pulse interference is entirely eliminated. This feature is extremely useful when the ARSR-2 is being operated near other radar systems operating on similar frequencies. It is also useful when friendly jamming missions are performed in the vicinity.

Angels

As mentioned above, small unwanted targets such as birds or insects plague the performance of a high-performance radar. These small targets, which are most noticeable in the MTI video, are often referred to as "angels", a name that was applied before the source of these signals was known. To a radar operator, a seagull and an airplane often appear the same on the PPI, and radar operators would sometimes ask the pilot of an airplane flying towards what appeared as an "angel" on the PPI to identify the unknown target. The pilot, however, would be unable to see a large bird flying a mile below him, and would report back to the radar operator that there were no targets near him. Thus, the term angels developed.

Now that these unwanted targets have been identified, it is possible to cope with them. Even though a bird and an airplane may appear the same on a PPI, the reflected signal from even a small jet airplane such as T-33 is over 200 times stronger than the reflected signal from a seagull. It is thus possible to turn down the receiver gain at short ranges so that birds will not be seen, but desired targets will still be visible. This is done with STC (sensitivity time control). The STC circuit, which varies receiver gain according to range, can be switched in at will by the operator.

Figure 7 shows how birds can make a PPI presentation almost useless. These pictures were taken in Oklahoma City. The range is 25 nautical miles. The birds were probably mostly crows, with a few hawks and buzzards. Although this looks like a great number of birds, there is only about one target per square mile. Figure 8 taken immediately after Figure 7 shows the use of a nominal amount of STC — the amount of STC calculated to remove a bird the size of a seagull or a crow from the display.

On present radars which have conventional antenna patterns, the use of STC may solve one problem but create another — loss of desired targets at high elevation angles. It will be shown below how the special antenna pattern of the ARSR-2 permits the use of STC without the loss of desired targets.

Antenna

In the discussion of the MTI system it was stated that it is desired to have as high a ratio of target-signal to ground-clutter-signal as possible. This statement can be generalized to include other types of clutter, such as unwanted weak targets.

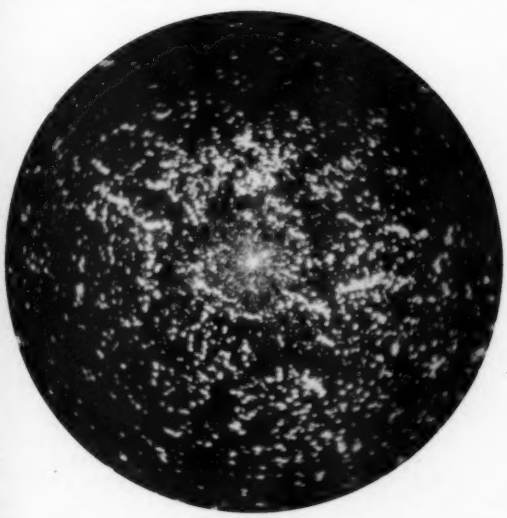


Figure 7.

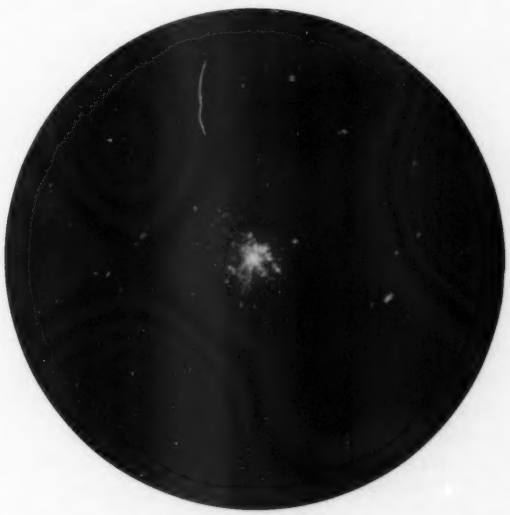


Figure 8.

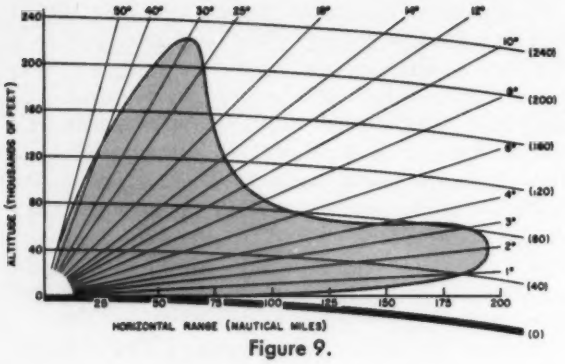


Figure 9.

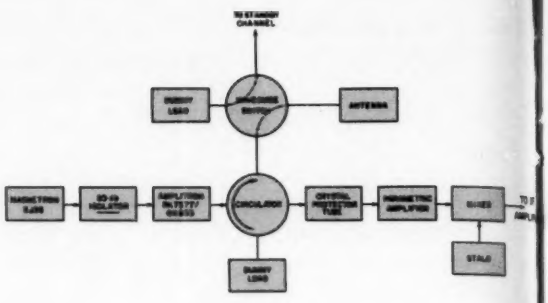


Figure 10.

Air route surveillance radars prior to the ARSR-2 have used antennas with a cosecant-squared pattern. This pattern results in antenna gain (above about 6 degrees elevation) being proportional to the square of the cosecant of the elevation angle. If the radar were used where there were no ground clutter signals and no undesired weak targets, this antenna pattern would be ideal, for it results in a constant strength signal return from an airplane flying at constant altitude, whether the airplane is 10 miles or 100 miles from the radar system. Unfortunately, however, clutter signals in the peak of the radar beam are much stronger at short ranges than at long ranges. Thus, with a cosecant-squared pattern and a target flying at constant altitude above 6 degrees elevation, the shorter the range, the lower the target-signal to clutter-signal ratio.

Since the use of STC and MTI both depend on maintaining an adequate target-signal to clutter-signal ratio, a special antena pattern was derived for the ARSR-2 to do this.[2]

The new antenna has a beam shaped so that relatively little energy is transmitted toward the ground clutter, but just a few tenths of a degree above the ground there is almost peak transmitted energy. At high elevation angles, the ARSR-2 also transmits considerably more energy than a system with a conventional antenna. The considerable improvement thus gained in target strength relative to clutter strength gives the ARSR-2 considerably better coverage at high elevation angles than previous air route surveillance radars. Comparison under assumed strong clutter conditions shows the ARSR-2 will provide coverage up to an elevation angle of 32 degrees on a small jet airplane, whereas the ARSR-1A, under the same conditions, would provide coverage up to only 12 degrees. The ARSR-2 free-space coverage diagram is shown in Figure 9.

Circular Polarization

The controller at the master console can instantly switch from linear to circular polarization to reduce the radar signal from rain, thus making it possible to see targets which would otherwise be obscured on the PPI. When the circular polarizer is utilized, it automatically absorbs 99 per cent of the receiver energy reflected from raindrops, but allows other received energy to enter the receiver. Thus the signal received from rain is attenuated by 20 db before entering the receiver, but signals received from aircraft are essentially unattenuated. Usually, the use of STC will be sufficient to prevent the remaining rain signal from

[2] (See "Antenna Considerations for Surveillance Radar Systems," by W. Shrader, Proceedings of the Seventh Annual East Coast Conference on Aeronautical and Navigational Electronics, October, 1960.)

INVENTIONS

Congratulations to the following persons for their valuable contribution to Raytheon's portfolio of inventions:

Name	*Field of Invention*
W. Beust	Variable Reactance Diode Modulator
T. R. Boughnou	AM or FM Sideband Cancellation System
J. E. Cline	Fabrication of Tunnel Diode
T. F. Cocca	Alloying Method
J. C. Davis, Jr.	Diode Rate Counters
J. C. Davis, Jr.	Electro-Optical Switch
J. C. Davis, Jr.	Meter Scale
A. W. Ede	J-Finger Delay Line Termination
W. T. Eriksen	Avalanche Transistors
I. Goldstein	Ferrite Modulator
B. Hecht	Point-Contact Tunnel Diode
W. J. Heinecke	Surface Stabilization of Semiconductor
C. J. Kieffer	AC Voltage Regulator
L. F. Kilham	ThermInductor
A. C. Marchetti	Transistor Voltage Alarm
R. Nelson	Semiconductor Micro-Plating
J. M. Osepchuk	M-Type Tubes Operating in a Cyclotron Mode and Utilizing Sorting and Slow-Wave Structures
W. Rindner	Semiconductor Micro-Plating
G. Rupprecht	Point-Contact Tunnel Diode
T. C. Taylor	Fused Contacts
T. Temple	AC Voltage Regulator
T. Temple	Transistor Voltage Alarm
R. T. Tuinila	Mandrel for Pyrographite
F. T. Wimberly	Missile Seeker

being displayed on the PPI. A controller at Boston's Logan International Airport has gone on record as saying that if the circular polarizer won't eliminate the rain return, the rain is too heavy to fly an aircraft through.

RF Portion

The simplified block diagram shown in Figure 10 indicates the major RF portions of the ARSR-2. The magnetron peak power output is 500 kilowatts, and the Amplitron peak power output is 5 megawatts. The circulator and isolator each have slightly less than 1 db insertion loss. Peak power at the antenna is about 4 megawatts. The system incorporates a non-degenerate, varactor parametric amplifier and the system noise figure, measured from the circulator output to the IF amplifier output, is 3.5 db.

Master Console and Video Mapper

The master console, shown in Figure 11, has a 16-inch CRT, an electronic cursor with bearing and range counters, complete controls for operation of the transmitter-receiver equipment, and panel lights to indicate any deterioration in the selected channel's performance.

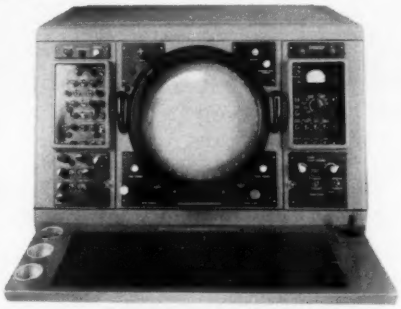


Figure 11.

Each console, whether master or auxiliary, has controls for setting the range at which MTI video ceases and normal or integrated-normal video starts In addition, gain controls are available on all consoles to provide a normal video background for MTI video and to introduce as much map and beacon video data on the PPI as desired.

The electronic video mapper is supplied in duplicate with each system. The map is displayed on the PPI with the radar video. If the operator changes the range setting or decenters the display, the map changes accordingly so as to maintain correct relationship with respect to the radar pattern. Another feature is an electronic cursor which enables the operator to determine range and bearing between any two points on the display. Because the cursor is electronically generated, the display can be decentered or the range changed without affecting accuracy.

ARSR-2
DETAILED CHARACTERISTICS

RECEIVER-INDICATOR

Console	16-inch PPI with P7 Phosphor
Sweep Rotation	Fixed coils and sweep resolver
Sweep Ranges	25 n. miles 50 n. miles 100 n. miles 200 n. miles } With one-radius off-centering on all ranges
Types of Presentation	Normal Video Integrated Normal Video MTI Video Beacon or IFF Video Video Map Adjustable Combinations of the above
Cursor	Electronic cursor with adjustable origin, range, and bearing
MTI Feature	3-pulse canceller with 3-period staggered repetition rate and feedback for velocity response shaping. Blind speeds at 0, 560, and 1120 knots.
Anti-Clutter Features	I AGC, STC, FTC, and circular polarization
System Noise Figure	3.5 db

TRANSMITTER

Peak Transmitted Power	4 megawatts
Pulse Repetition Rate	360 pulses per second average, 3 periods staggered (stagger ratio is 6:7:8)
Pulse Width	2 microseconds
Frequency Range	1280 to 1350 megacycles
Source of RF Power	5J26 tunable magnetron driving QK653 Amplitron

ANTENNA

Gain	34 db
Beamwidth	Horizontal: 1.2° Vertical: 3.75°, specially shaped to 45°
Antenna Rotation Speed	5 RPM
Reflector	46 feet by 23 feet
Antenna Feed	Horn feed; with choice of horizontal-linear or circular polarization remotely controlled.

Conclusion

The ARSR-2 system offers increased transmitter power, an improved antenna system and advanced circuits for eliminating clutter and interference. These features will result in improved detection range and target visibility — a capability of growing importance in the jet age. Air traffic controllers will soon be keeping the nation's airways under surveillance with the finest radars ever designed for this purpose.

RESEARCH IN PLASMA PHYSICS

Introduction

Within the past decade, attempts to control thermonuclear fusion and the emphasis on space technology have increased the interest in plasma physics. Many scientists are thoroughly investigating the unique properties of plasmas, both theoretically and experimentally. Extensive research is under way to better understand the naturally occurring plasmas and the interaction of plasmas with electromagnetic waves; the direct conversion of solar and chemical energy into electrical energy; and techniques for plasma diagnostics.

A plasma can be described as a collection of ions, free electrons, and neutral atoms which may exist in solids as well as in gases. Because the electron and ion densities are usually extremely large in a plasma and the charges are relatively mobile, large potential gradients cannot exist unless very large plasma currents flow. Poisson's equation indicates that because of the small electric field components, the net charge density is small. Thus, the electron and positive ion densities in the plasma are usually approximately equal to each other to within a small fraction of a percent.

Some of the basic processes in a plasma can be illustrated by a short discussion of an electrical discharge through a gas or vapor in a cylindrical glass tube. An example is the discharge occurring in a neon light or a fluorescent light. In this case an axial electric field supplies energy to the plasma electrons at a rate proportional to the drift velocity of the electrons and to the electric field gradient. The plasma ions also gain energy from the field, but at a much lower rate because of the much lower ion drift velocity.

The electron-electron interactions cause the electrons to approximate a Maxwell-Boltzmann distribution function which describes the distribution of energy among the electrons. The high-energy elec-

SOL AISENBERG *is a Staff Member in the Research Division. Since joining Raytheon in 1956, he has done research in paramagnetic resonance, paramagnetic relaxation, Masers, and photoemissive solar energy converters. At present, he is investigating plasmas and associated problems. From 1951 to 1956 he was a research assistant in the Physics Department and the Research Laboratory for Electronics at M.I.T. While at M.I.T., Dr. Aisenberg did research in physical electronics, including low pressure plasmas and the theory of probe analysis of plasma properties. He received his B.S. degree in Physics from Brooklyn College and earned his Ph.D. in Physics from M.I.T. in 1957.*

trons of the distribution ionize the gas atoms and also produce excited atoms which give off radiation as they drop down to lower energy levels.

The positive column of the plasma has certain unique properties. Because the plasma electrons are more energetic than the ions the electron random velocity is much larger than the ion random velocity. Thus, the random electron current to the boundary is much larger than the random ion current, and the insulating boundary acquires a negative potential relative to the plasma. The ions tend to remain behind so that the plasma acquires a slight net positive charge. This positively charged plasma is often referred to as the plasma positive column. The negative potential of the boundary repels some of the lower energy electrons and also increases the flow of positive ions until the electron and ion current flow are equal. When this happens the boundary has reached its floating potential, and a radial potential gradient and a radial density gradient are set up in the plasma. In the plasma sheath (the transition region between the plasma and the boundary), the electron density is much less than the ion density, and the potential gradients are large.

The flow of ions and electrons (in the range where the mean free path is small compared to the tube size) can be described by mobility and diffusion processes. Mobility flow corresponds to an average drift velocity component due to an electron potential gradient, while diffusion flow corresponds to a drift velocity component due to a density gradient. The flow equations are nonlinear, but with the appropriate approximation a set of linear ambipolar flow equations can be obtained. Many other processes occur in the discharge tube. The items described here, however, are the most significant and should give a feeling for some of the physics involved.

History of Plasma Research

Much of the early important progress in plasma physics was due to the work of Langmuir and his colleagues who investigated, among other topics, the problems of the plasma positive column, the plasma sheath, and probe measurements of plasma properties. For example, Langmuir showed that correct analysis of the retarding potential plots of a probe in a plasma could be used to deduce much information about the properties of the plasma. The early research featured the theoretical study of solutions of the Boltzmann transport equation, and studies of the arc discharge, the glow discharge, and high voltage DC breakdown. The Boltzmann transport equation is one of the most important concepts in plasma physics since it describes the motion of electrons in configuration and velocity space. The Boltzmann equation is a nonlinear, integral-differential equation which has been solved only in approximate forms. Its solutions can, in principle, describe the motion of electrons as a result of potential gradients, density gradients, and temperature gradients. The high-energy tail of the electron distribution function can be used to compute ionization and excitation of atoms in the plasma. Langmuir and Tonks (and others) also investigated the problem of plasma oscillation and, in particular, the effect on the conversion of directed electron energy into random electron energy. Apparently, plasma oscillations may be a major factor in the production of the high-energy tail of the Boltzmann distribution function.

From the work of Debye and Hückel on ions in electrolytes, the important concept of the Debye length was introduced into plasmas. According to the Debye-Hückel theory, the normal coulomb potential of a charge is modified by a shielding term which corresponds to the tendency of thermal energy particles of the opposite charge to cluster in the vicinity of the original charge being shielded. The Debye length is a characteristic distance in the exponential shielding term and corresponds to the radial distance for the normal coulomb potential to be reduced by a factor of e, the base of the natural logarithm. The concept of the Debye length is important for plasma phenomena near boundaries and also for the scattering of charged particles by other charged particles in a plasma.

A considerable portion of the early work in plasmas was of a basic nature in the sense that the fundamental parameters for collision, ionization, radiation, excitation, absorption, recombination, dissociation, and scattering processes were investigated both experimentally and theoretically. Surface interactions were also studied; in particular, secondary electron emission due to electron and ion bombardment. Attention was also focused on the problem of ion and electron mobilities, diffusion coefficients, and ambipolar diffusion.

The need to understand the mercury arc rectifier, the thyratron, and gas discharge lamps was responsible for some of the early scientific activity in plasmas. Astrophysical research involving theoretical study of the sun has lead to significant progress in plasma physics. For example, the Saha equation decribes, from a thermodynamic point of view, the thermal ionization of an extremely hot gas. Experimental work has involved the study of the high-pressure arc and the study of basic processes in the sun. Mathematical analysis of transport processes in gases by Chapman and Cowling was of great importance to plasma physics in general. Early work on the reflection of radio waves from the ionized layers in the

earth's atmosphere emphasized the interaction between electromagnetic waves and plasmas. The cross modulation of radio waves in the ionosphere (the Luxemberg effect) was also observed and investigated.

Present and Future Areas of Plasma Research

The early research furnished the scientific basis for the explosive growth of activity and interest in plasmas. To a large extent, the increased activity is due to the realization that plasmas are important from a practical aspect and may become even more important. Some of the recent work and potential areas of activity will be described in order to show the importance and potentialities of modern plasma physics.

Thermonuclear Fusion Plasma Physics

Probably the most important programs in development and research are in thermonuclear fusion plasma physics. The problem in fusion research is to obtain a high-temperature (about 10^{8}°K), high-density (10^{14} to 10^{18}/cm^3) hydrogen plasma for an adequate length of time (approximately 1 second) so that sufficient fusion can occur to result in a net energy gain. Because of the very high temperatures required, it is difficult to confine the plasma in order to prevent loss of the plasma energy and to prevent destruction of the vacuum container walls. Use of magnetic fields for plasma containment is an important part of the fusion program. Most types of fusion plasmas in magnetic fields, however, show strong instabilities which result in the loss of the desirable plama conditions.

Heating of the plasma is sometimes accomplished by the ohmic effect of strong currents through the plasma. Unfortunately, this method results in heating of the electrons, and the resulting radiation of energy by these high-velocity electrons is responsible for a prohibitively large energy loss. Another way of heating the plasma is by compression through an increase in the trapping magnetic field. This also results in high-energy electrons. Since it is only the hydrogen ions that must have high relative velocity (to overcome the repulsive forces) and since the energy loss by the electrons is much more important than the loss by the ions, it appears preferable to feed the energy directly into the ions and to depend on the "ion energy-electron energy" transfer processes to limit the electron energy and the resulting electron energy losses. Note that the presence of electrons is necessary in order neutralize the ion space charge, otherwise large potential gradients would result; the problem is to keep the electron energy low.

Normally the energy losses due to impurities also are a serious problem. Impurities in a thermonuclear plasma are troublesome since the electron energy loss due to almost fully ionized impurities increases as Z^2, where Z is the atomic number of the impurity. If the electron energy is reduced, the loss due to impurity scattering of electrons will not be as important as it is in the hot electron plasma.

One way of selectively obtaining high energy ions is to inject energetic ion beams into a magnetic mirror structure. The problem of ion injection is to prevent or minimize the reverse process of ion ejection. The loss of ions in spite of the confining magnetic field can arise through diffusion across a magnetic field (which is not really well understood at the present time) and through charge exchange processes where the energetic ion exchanges charge with a low energy neutral particle. The resulting high energy neutral particle and the low energy ion are both able to pass out of the confining magnetic field. The possibility of electromagnetic containment of the plasma is still being investigated.

A very attractive way of selectively heating the ions in a confining magnetic field is to use ion cyclotron resonance so that the ions can gain considerable energy from a intense RF field. The RF frequency should be high compared to the gas collision frequency so that, for reasonably dense plasmas, a high frequency RF field and very intense magnetic fields are required. If the ions can be made to move with varying phase, then the relative velocity of the ions will be large and a randomization of the ion energy will not be necessary.

In addition to the major effort in fusion plasma physics, there is considerable effort being expended on other problems, many of which are related to the advent of the space age and the growing importance of electronics. These problems will be outlined in the following groups, although there are cases that overlap and cases that could also be included in other groups.

The Plasma LASER

Recently, Bell Telephone Laboratories has demonstrated a working model of the Plasma LASER (Light Amplification by the Stimulated Emission of Radiation). The output of this device is extremely monochromatic and has a very narrow angular dispersion. The operation of the Plasma LASER (PLASER) is approximately as follows. Energetic electrons (generated by an RF discharge) produce numerous metastable states in a suitably chosen gas, which excite a second suitably chosen gas also present in the discharge plasma. The excited atoms drop back to the ground state through intermediate states, and if the lifetimes of the intermediate states have the proper

values, a significant population inversion of these states may occur. This population inversion corresponds to more atoms in a higher state than in a lower energy state. If the plasma discharge takes place in a tube whose end plates are extremely parallel, smooth, and highly reflective, the spacing of the end plates can be adjusted so that the enclosure acts as an extremely high Q resonant structure at a frequency corresponding to a population inversion. The light bouncing back and forth through the discharge will induce transitions between the inverted levels with a resulting amplification of the light intensity. The discharge can be operated continuously so that the optical output can be an intense, narrow, continuous beam of very monochromatic optical energy. Some of the possible research problems connected with the Plasma LASER may involve: the selection of gases or vapors to give better output; the coating of the discharge tube walls with paraffin type compounds to reduce the loss of metastables and excited states at the walls; and the addition of another gas component to quench the lower energy states so as to enhance the population inversion. A major problem connected with the utilization of the potentially large bandwidth for communication purposes involves the wide-band modulation and demodulation of the optical beam. The extension of the Plasma LASER principle to the millimeter and submillimeter range offers some interesting challenges.

Space Electronics and Associated Problems

Many plasma physics problems are connected with space electronics. Solar electrons that are trapped in the earth's magnetic field result in the Van Allen layers of plasma around the earth. Atmosphere plasmas generated by hot re-entry objects and missiles produce problems connected with the preservation of the re-entry object. There are accompanying problems of telemetering through the re-entry plasma and of detecting the re-entry objects by means of their re-entry plasmas. Exhaust jets of rockets are plasmas because of their high temperatures; a problem here is connected with the possibility of detecting rockets by means of the plasma properties of the exhaust jets. Space systems using ion beam propulsion, plasma propulsion, and exploding wire plasma propulsion, may also have strong potentialities.

Shock tube research, in addition to producing and investigating hot plasmas, is directed to the study of plasmas associated with high velocity objects, such as space vehicles. The plasma arc jet is a source of very high temperature plasmas, and can also be used for testing high temperature materials. By means of the RF plasma torch, where the gas is ionized by RF induction fields, one can obtain extremely high temperatures (temperatures of 20,000°K have been reported and temperatures of up to 100,000°K are expected in the future). The plasma torch can be used for testing high temperature materials and has been used for growing single crystals. Single crystals with desirable properties may also be grown using ion beams and plasmas. By using plasmas one may make high intensity, short duration, light sources. Plasmas may function as efficient ion sources for use in research on sputtering of space age materials. If the gaseous breakdown by strong RF and DC fields can be better understood, it will then be possible to control and use these breakdown plasmas. More information about the plasma sheath associated with the re-entry object will be necessary in interstellar flight. The use of ball lightning will probaby be important after an improvement in the understanding, production, and control of this phenomena.

Energy Conversion Using Plasmas

The prospect of using plasmas in very efficient and compact devices to convert solar energy or chemical energy into electrical energy has considerably increased activity in this area. Chemical energy may be directly converted into electrical energy using magnetohydrodynamics; this involves the conversion of the momentum energy of an ionized gas into electrical current flow by means of magnetic fields. A very important approach to the direct conversion of thermal energy into electrical energy involves the use of a cesium plasma diode. This method has promise of being reasonably successful in the near future.

Interaction of Electromagnetic Waves with Plasmas

Because of their strong interaction with electromagnetic waves, plasmas are an important factor in communications. The problems of electromagnetic propagation and absorption in plasmas are being studied. The growing waves present in plasmas are of particular interest since these have possibilities for microwave generation and amplification, especially in the millimeter and submillimeter ranges. Artificial high altitude plasmas may be generated and controlled by intense beams of microwave energy. Plasmas may be used as noise generators in the low frequency and microwave ranges. The plasma noise characteristics may also be used to effectively measure plasma temperatures and other discharge properties.

The problems associated with plasma oscillation and radiation in the millimeter range are the excitation of plasma oscillations and the coupling of RF energy from the plasmas. Perhaps one can use normal sized cavities filled with plasma which can propagate very high frequencies. There is a possibility of effectively exciting plasma oscillations in semi-

conductor plasmas (electron-hole plasmas). Fully ionized plasmas (e.g., cesium) are attracting a great deal of interest, since much of the theoretical work dealing with fully ionized plasmas may now be tested. In addition, these highly ionized plasmas may be of value in generating millimeter and submillimeter power. If one injects electron beams into these highly ionized plasmas, the absorption of the beam energy by the un-ionized gases is essentially nonexistent, while the interaction of the electron beam and the charged particles of the plasma is dominant. Hence, one has a very effective way of converting electron beam energy into plasma oscillation energy. Very high frequencies of plasma oscillations can be obtained if very dense plasmas can be obtained. Many processes in plasmas are nonlinear; if these nonlinearities can be strongly emphasized it may be possible to effectively produce harmonics. This may be of importance in generating millimeter waves. It may also be possible to develop efficient demodulators of microwave energy using plasmas. The advantage of such a demodulator structure is that it would be relatively insensitive to extreme power overloads. The noise problem, however, may present difficulties.

Techniques for Plasma Diagnostics

One of the major limitations to effective experimental work in plasmas is the difficulty of measuring some of the fundamental properties and processes of the plasma. Probe techniques, microwave techniques, and radiometer diagnostics techniques are useful over only limited ranges. The interaction of electron beams with plasmas can be used to deduce plasma properties. In addition, the plasma conductivity in magnetic fields can be used to study the tensor properties of plasmas. The development of new diagnostic techniques would be of considerable help in the progress of plasma research.

Some of the fields mentioned are redundant, in the sense that progress in one area can be used in other related problems. Many of the research projects described require careful coordination of basic experimental work plus detailed theoretical analysis of the physics involved. The total effort being expended on development and research in plasma physics is considerable in the scientific world and will become even more important as further successful work is completed.

Current Raytheon Work

Plasma research is being conducted by Raytheon in a number of its divisions. In particular, the Research Division — in an intergroup effort — is constructing a Plasma LASER. The plasma group in the Research Division is also performing Langmuir and Druyvesteyn probe analysis of plasmas. From this latter work we expect to obtain information about the electron energy distribution function, the charge generation, and the charge transport processes in the plasma. In addition, we shall investigate ion cyclotron resonance and other processes involving the interaction of microwaves and plasmas.

A number of key publications dealing with plasma physics are given in a list for general information.

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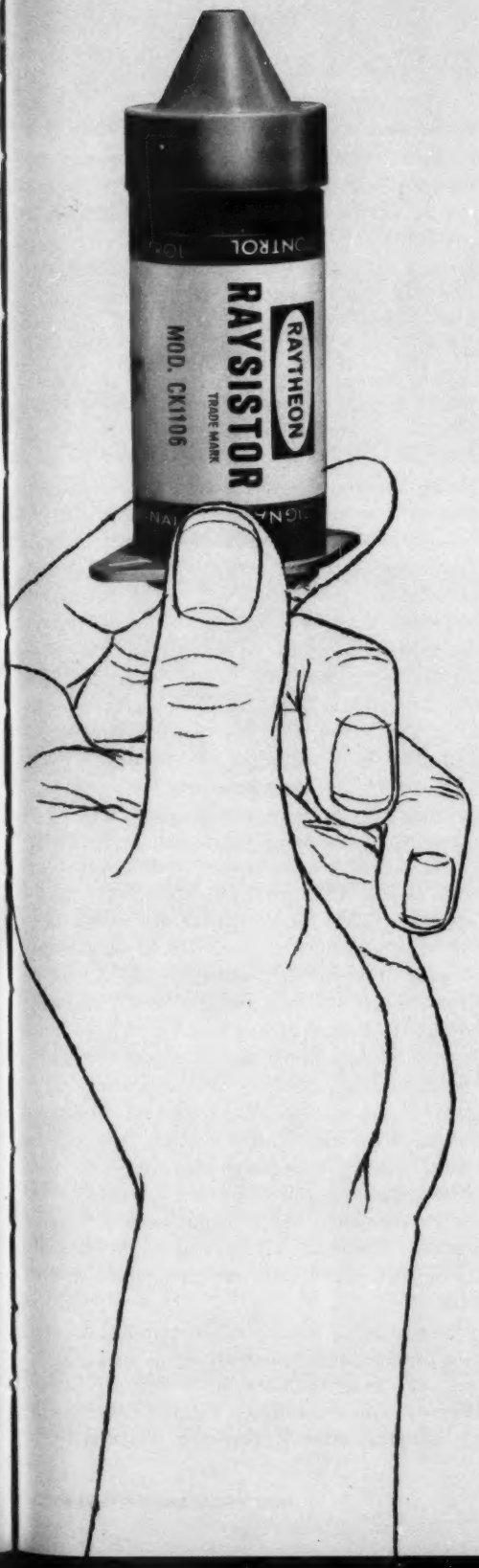


PHOTO-CONDUCTORS

CHARLES W. CARRUTHERS *is Chief Engineer of the Electromechanical Components Operation, Industrial Components Division. Before joining Raytheon in 1954, he served as a physics instructor at Bates and Bowdoin Colleges. His initial assignment in the Missile Systems Division consisted of organizing a Microwave Tube Test Section, setting up the physical facilities, training personnel and preparing procedures and specifications. He has also studied the problems of ion propulsion device design for use in space systems. Mr. Carruthers received an A.B. degree in Physics from Bowdoin College and has done graduate study at Harvard and Northeastern Universities.*

Introduction

Recently, Raytheon Company placed on the electronic components market a new device called the RAYSISTOR. This device consists of a light source and a photoconducting cell housed in a small tubular shield; a variation in the light source drive causes a variation in the cell's conductivity. The RAYSISTOR may be used as an electrically driven chopper, relay, potentiometer or rheostat.

The circuit engineer who attempts to apply components containing photoconductors is likely to encounter many seemingly unrelated effects unless he is familiar with the basis for their behavior. For example, the illuminated or "on" resistance increases with temperature, while the dark or "off" resistance decreases with temperature. A temperature change may increase the "turn on" time, but decrease the "turn off" time or vice versa. The "turn off" time appears to decrease with an increase in the "on" illumination level, though actually the time needed to reach a given value of "off" resistance is nearly independent of the previous illumination level. A photoconductor may exhibit a variety of memory effects. The nature of the contact materials determines whether the current varies as the first, second, or some other power of the applied voltage. The spectral sensitivity may be quite narrow and, in fact, photoconductivity may be inhibited by radiation outside this range.

Photo-Effect Devices

To establish properly the unique position of the recently developed photoconducting cells, it is desirable to review and classify some of the more common photo-effect devices. A starting point is to consider the class of phototubes based on the use of a photoemissive cathode. In general, for a fixed supply voltage, the output current of this class of phototubes is a linear function of the light intensity over a wide range. The reverse is not true; that is, with a fixed light intensity the output current is not a linear function of the supply voltage. The impedance of a high vacuum phototube is extremely high, but not of serious consequence in many vacuum tube circuits. Use of a gas filling to allow current multiplication within the phototube affords a much lower output impedance but with considerable sacrifice in speed of response.

The secondary-emission multiplier type of phototube has reached a high state of development and is particularly useful in certain scientific applications, such as observing the light from a distant star or the scintillation produced from the passage of a single high-energy particle in a suitable cell. The very high current amplification which takes place in the multiple-cathode array would be difficult to achieve in conventional amplifier circuits without instability. Unfortunately, the total supply voltage required is quite high (often several thousand volts) and limits the application to those cases where other methods are impractical. The widespread use of photomultiplier tubes in scientific instrumentation, has led to the development of a wide variety of primary photo cathodes, each having a particular spectral response.

For almost a century, it has been recognized that selenium as well as certain metal oxide and sulphide compounds exhibit a light-sensitive electrical behavior. These materials have been used in a variety of photovoltaic and photoconducting cells. Such devices have been employed directly with meter movements, as in photographic exposure meters, and with moderate polarizing voltages to operate sensitive relays for the control of lighting and alarm systems. In general, the operation of these photoconducting devices does not depend on linear relations between the output current and either the light intensity or the applied voltage.

During the last decade, the more commonly known semiconductor materials — such as silicon and germanium — have been utilized in photosensitive diode, triode, and tetrode device configurations. Typically, these materials require one or more polarizing or bias voltages to set up the operating conditions. It also is necessary to use rectifying or non-ohmic contacts on the semiconducting material, since the resistivity of the material itself is quite low. This is true in the dark condition at room temperature or above. With a symmetrical arrangement of electrodes, a pair of diodes that will provide the same behavior for voltages of either polarity may be constructed on a single chip of semiconducting material. Unfortunately, saturation effects set in with only a fraction of a volt applied, and above this voltage the current depends only on the light intensity. This would not be serious if large swings in conductivity (ratios of 10^6 or more) were obtained with practical light sources, since a load resistor several times the value of the "on" resistance could be used to obtain an appreciable voltage across the load. Actually an on-off ratio of about 10^3 is commonly attained, and therefore the saturation effects must always be considered. The major advantages of these devices are their relatively small encapsulated size (about $\frac{1}{16}$ of an inch in diameter) and their speed of response (in the microsecond range). Like vacuum tube photocells, their output usually requires amplification. They are often used in applications requiring a high speed decision between on and off conditions.

With the coming of homing missiles and space vehicles, two other photo-effect devices — the infrared detector and the photovoltaic solar power cell — have received considerable attention. Infared detectors for military use must have a maximum sensitivity, or

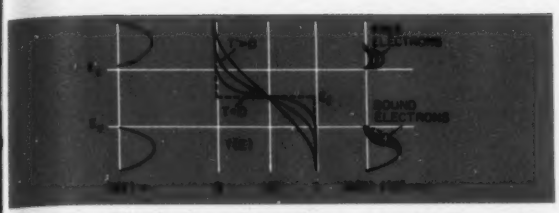


Figure 1. Distribution of possible states, N (E), probability, f (E), and their product, N (E) · f (E), to obtain the probability distribution of occupied states in the conduction and valence bands (intrinsic semiconductor)

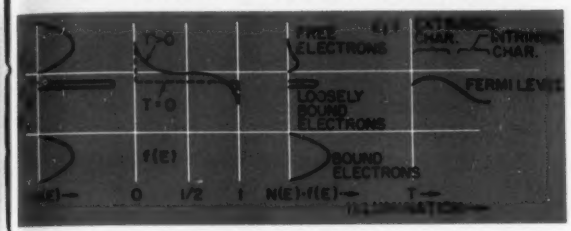


Figure 2. Probability distribution with a donor impurity added (n-type semiconductor), and changing Fermi level with temperature or illumination

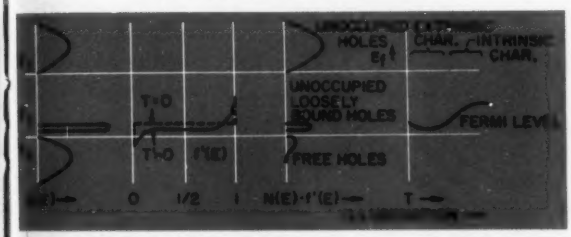


Figure 3. Probability distribution in a p-type semiconductor, and changing Fermi level with temperature and illumination

signal-to-noise ratio under low incident power levels; often requiring that the detector be cooled to the temperature of liquid nitrogen. Since the most important energy source for space vehicles is solar radiation, the construction of photovoltaic cells which will efficiently convert this radiation into electrical energy has been a major goal. Refined as they may be these devices are not suitable for electro-optical relay circuit applications.

Other photoconducting cells, such as those used in Raytheon's RAYSISTOR, are made of cadmium sulphide or cadmium selenide in a thin, sintered polycrystalline layer. These cells employ ohmic contacts and behave as an almost pure resistance over any practical signal range from microvolts to kilovolts. Their conductance may be controlled by the illumination level over a range of more than six orders of magnitude. Presently-available cells exhibit a response time that is short compared to that of human beings but longer than the more commonly used vacuum tube and semiconductor amplifying devices.

Intrinsic Material

It would perhaps be advantageous at this point to review some of the physical concepts related to semiconductors. Let us consider an intrinsic (i.e., pure) semiconducting material having no defects or discontinuities within its crystal lattice. We will also assume that the material is not subject to external influences, such as elecric fields, magnetic fields, light flux, or high energy particles. The number of charge carriers and consequently the conductivity of the intrinsic material depends on two factors. One of these factors, the band gap (width of the forbidden region between possible electron energy levels), is a property of the material. The other, the temperature, is a condition imposed on the material. The band-gap property is illustrated in Figure 1, where the function N(E) indicates the distribution of possible energy states in which electrons may reside. If the valence energy band is completely filled, that is, if there are electrons possessing all possible energies up to the level E_v, then there can be no conduction current produced by these electrons. This follows from the fact that a conduction current would require a systematic drift of electrons in a particular direction which in turn requires that the electrons possess additional energy above and beyond the possible energy states. However, electrons in an unfilled conduction band having an energy greater than the lower band edge, E_c, are free to take on additional energy and provide conduction currents under the influence of an electric field. In the steady state, no electrons may possess an energy within the band gap between E_v and E_c. The family of curves f(E) in Figure 1 relate the temperature to the probability that an energy state (if it exists) will be filled. Thus, within the band gap we have the seemingly peculiar situation that while the probability of a given state being filled is precisely determined by the temperature there are no possible states. In this sense, it may be easier to think of the probability function, f(E), as a weighting function. The product of N(E) · f(E) gives the distribution of occupied states; the temperature dependence of this product is shown in Figure 1 by a family of curves.

Mathematically, the function f(E) may be expressed as:

$$f(E) = \frac{1}{1 + e^{\frac{(E - E_f)}{kT}}} \quad ,$$

where k is Boltzmann's constant, T is the absolute temperature, and E_f is the Fermi level. The Fermi level, which is a constant for a pure material in the absence of external influences, is that value of the energy E for which the expression f(E) is equal to one half.

At a given temperature, the extremes of semiconduc-

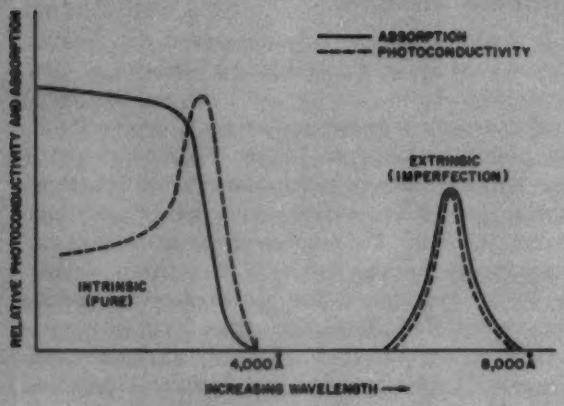


Figure 4. Typical response vs. wavelength

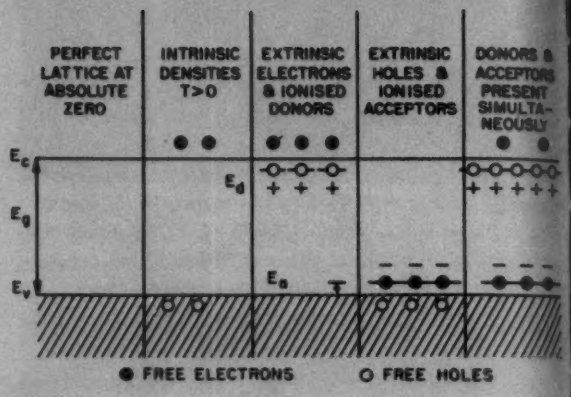


Figure 5. Example showing the effects of the presence of both donors and acceptors simultaneously

tor behavior (either approaching the low conductivity of an insulator or the high conductivity of a metal), may be interpreted in terms of band-gap width. If one were working with pure or intrinsic materials, he would choose a material (if available) having a band gap which would give the desired conductivity in its normal operating temperature range. (A wide band-gap material may have the same conductivity at high temperatures as a narrow band-gap material at low temperatures, although the temperature coefficients are likely to be different.) One of the first considerations in selecting a semiconductor for photoconductor use is that the band gap be large enough to provide the desired "off" or dark resistance at the operating temperature, which is usually somewhat above room temperature. In order for the absorption of a photon of light to create a free carrier and thereby increase the material conductivity, it must have an energy greater than or equal to the band gap; or:

$$h\nu \geq E_c - E_v \quad ,$$

where h is Planck's constant and ν is the frequency associated with the incident photon.

It may be considered as another example of the perversity of nature that a material having a band gap wide enough to secure high dark resistance will respond only to the high-energy (shorter) wavelengths of light toward the ultraviolet end of the spectrum. Actually intrinsic materials are seldom used for photoconductors; therefore, the simple picture must be replaced by a more complex one.

Extrinsic Materials

The crystal lattice of an intrinsic material may be disturbed physically by a dislocation in the regular array or by a discontinuity such as a surface or interface, and chemically by the inclusion of a relatively small quantity of another material called an impurity or a doping agent. Such a disturbed or doped lattice is known as an extrinsic material. Whatever the cause, some of the lattice sites will have either an excess of electrons (loosely bound electrons — n-type semiconductor) or a lack of electrons (loosely bound holes — p-type semiconductor). The effect of doping with donor (donating an electron) and acceptor (accepting an electron) impurities is shown in Figures 2 and 3. If the energy level of these loosely bound electrons (or holes) is quite discrete, then it may be represented by some average value, E_d. The energy gap between E_c and E_d may be quite small. Obviously, a much lower value of energy of the incident radiation will now suffice to liberate an electron (or hole) from the impurity level, E_d, and raise it to the conduction level, E_c (or the valence level E_v). In fact, the wavelength of the radiation may be in the infrared. A plot of response versus wavelength for both intrinsic and extrinsic materials is shown in Figure 4.

It is entirely possible to obtain a response in the infrared by using a narrow band-gap intrinsic material, but since many carriers are available thermally there would be only a moderate increase in conductivity when the illumination is turned on. Doping with only one form of impurity (for example, with donors of electrons) would have much the same effect over a restricted range of temperature and illumination as using a narrow band-gap material. However, if both donor and acceptor impurities are present, a sort of mutual ionization of donors and acceptors may take place without releasing any appreciable number of charge carriers. This effect is shown in Figure 5. A material doped with both types of impurities will still release charge carriers readily on illumination and hence exhibit both a high dark resistance and a low illuminated resistance. In the illuminated condition

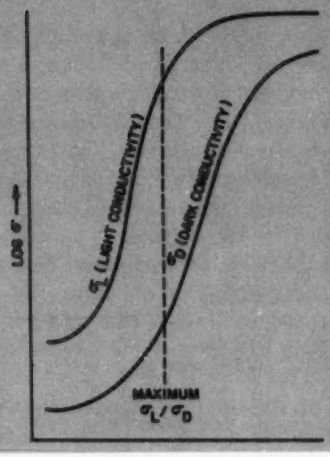
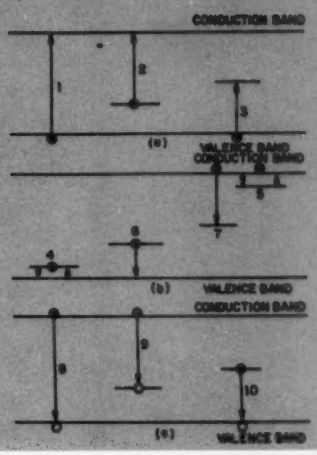


Figure 6. Increasing "X" doping ⟶
⟵ Increasing "Y" doping



(a) Absorption of a photon and excitation of an electron
1. From valence to conduction bands
2. From donor to conduction band
3. From valence band to acceptor

(b) Trapping and capture of electrons
4, 5. Trapping and thermal release
6, 7. Capture

(c) Recombination of an electron hole pair
8. Across the band gap
9, 10. Between band edges and recombination centers

Figure 7. Common electronic transitions in photoconductors

there is no longer a simple correspondence between the number of free electrons and free holes, thus it is convenient to consider the existence of separate Fermi levels for electrons and holes. The effect of doping with two different materials is illustrated in Figure 6. Increasing the "X" doping increases the "on" or light conductivity, σ_L, and increasing the "Y" doping decreases the "off" or dark conductivity, σ_d. In practice, these effects are sufficiently independent so that a highly advantageous ratio of light to dark conductivity may be obtained.

Several processes associated with photoconduction are illustrated in Figure 7. The first (Figure 7 a) is the absorption of a photon and the release of a charge carrier. This may take place at wavelengths shorter than the absorption edge by elevating an electron from the valence band directly to the conduction band. At longer wavelengths, absorption is still possible by the elevation of an electron from a donor level to the conduction band or by the elevation of an electron from the valence band to an acceptor level, thus producing a free hole. In the last two cases, the charges associated with the donor and acceptor levels are loosely bound and only the electron in the conduction band or the hole in the valence band is completely free. The second process (Figure 7 b), called trapping, occurs when a charge carrier is captured and bound momentarily at the donor or acceptor level only to be released by thermal excitation and return to the band from whence it came. A third process (Figure 7 c), is called recombination and occurs when a charge carrier or pair disappears from circulation permanently. The simplest but not always the most common case of recombination is that of an electron falling back from the conduction band and recombining with a hole in the valence band. Such a transition is indicated in some materials by a bluish electroluminescence. More often, in materials containing donor and acceptor impurities, the transition is between the band and an impurity level having a suitable mate available. There is no hard and fast distinction between impurity centers which act as sources (donors or acceptors), trapping centers, and recombination centers. Impurities close to the band edge are somewhat more likely to act as traps than as recombination centers; however, the role played may change with the carrier density and illumination level.

The difficulty of making a valid analysis of the events taking place is made more evident by the fact that with practical photoconductors the free-carrier density may change by more than six orders of magnitude between the illuminated and dark conditions. In this case, both Fermi levels and the demarcation levels between trapping and recombination vary over a considerable range. The mobility of the carriers may be altered by changes in scattering cross sections as the traps are filled or emptied. Even the term carrier lifetime, which seems to be almost self-explanatory, must be broken down into such qualifying forms as (1) free lifetime, (2) excited lifetime, (3) pair lifetime, (4) minority carrier lifetime, and (5) majority carrier lifetime. At this point, it seems to be more useful to turn to the examination of empirical results.

Empirical Results

Perhaps the behavior aspect of photoconductors most annoying to the circuit designer is the slow speed of response to changes in the illumination level (Figure 8). This behavior may be explained in terms of trapping effects. As the illumination level is increased, additional traps are filled, and as the illumination level is decreased, the traps gradually empty under thermal excitation. The effect is somewhat like the charging and discharging of a capacitor except that

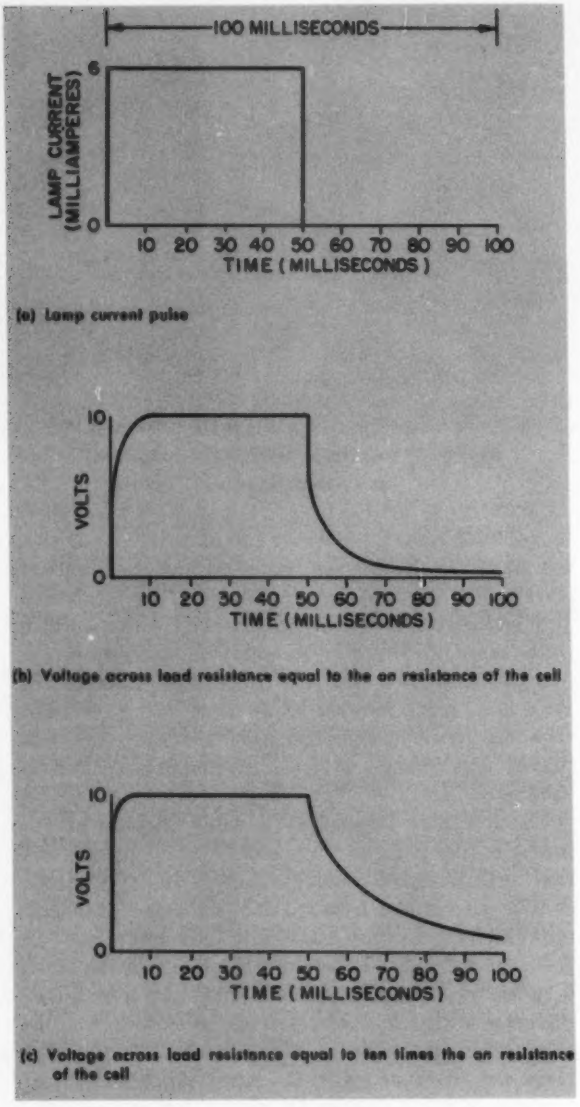

100 MILLISECONDS
LAMP CURRENT (MILLIAMPERES)
6
0
10 20 30 40 50 60 70 80 90 100
TIME (MILLISECONDS)
(a) Lamp current pulse
VOLTS
10
0
10 20 30 40 50 60 70 80 90 100
TIME (MILLISECONDS)
(b) Voltage across load resistance equal to the on resistance of the cell
VOLTS
10
0
10 20 30 40 50 60 70 80 90 100
TIME (MILLISECONDS)
(c) Voltage across load resistance equal to ten times the on resistance of the cell

Figure 8. Photocell response time

the value of the capacitance is not fixed and the charging and discharging resistances are not equal. An increase in the temperature will speed up the process of emptying the traps, but does not increase the filling time to any marked degree. Increasing the temperature thus increases the speed of response (Figure 9). In chopper applications where the modulation efficiency is frequently limited by the speed of response, an increase in temperature may result in considerably more output. Unfortunately, present-day materials do not allow a sufficient increase in temperature to increase the speed of response by more than a factor of two or three over the room temperature value. As higher and higher illumination levels are used, the relative influence of the traps decreases since the majority of the charge carriers will have to recombine directly and only the remaining "tail end" will be released from the traps (Figure 10). Thus a greater percentage change in resistance may be obtained in a short time interval following "turn off" if higher levels of illumination are used, but this has no effect on the time taken to reach some higher value of resistance. It has been suggested that an infrared source be used to promote the rapid emptying of the traps. To do this, it would be necessary to devise a fast-acting lamp which gives visible light when "on" and an intense infrared light in "stand by."

The curve of Figure 11 shows the resistance of a photoconducting cell versus the lamp current. (Illumination from a neon lamp is roughly proportional to the current over a considerable range.) A saturation effect is indicated which may be attributed either to the limited availability of suitable donors and acceptors, or to an increase in scattering cross sections or other carrier density effects. A more important relation for the circuit designer is the excellent linearity displayed in the curves relating the voltage to current at a given illumination level (Figure 12). The combination of ohmic, non-rectifying contacts on a polycrystalline material results in almost purely ohmic behavior, with no measurable photovoltaic output even with non-uniform illumination of the cells' surface. In general, cadmium sulphide and cadmium selenide behave as n-type or donor materials and require a material of lower work function for ohmic contacts. Indium and gallium both satisfy the requirements but since gallium melts at about room temperature, indium is commonly used. Indium melts at 155°C and probably will diffuse slowly into the cell at temperatures above 100°C, therefore it is common practice to limit operation to ambient temperatures below 75°C.

Cell Geometry

If the specific cell characteristics required in a certain application are not available, one should examine the possible effects of geometrical factors before starting on a quest for new materials Not only is this true from an economic standpoint, but also from the certainty of outcome. Although it is natural to expect that the conductivity will vary with cell geometry, it is quite surprising to find that the geometry also may indirectly affect the "on-off" ratio and the speed of response. The cardinal principle in cell design is to avoid any poorly illuminated areas on the active portion of the cell, since such areas cannot contribute to "on" conductance but must contribute to the lowering of the "off" resistance. For example, if the active material were made so thick that most of the light were absorbed near the outer surface, little

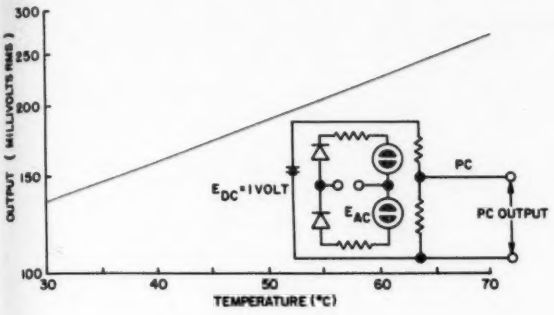


Figure 9. Increase in modulator output with temperature results from an increase in the speed of response with temperature

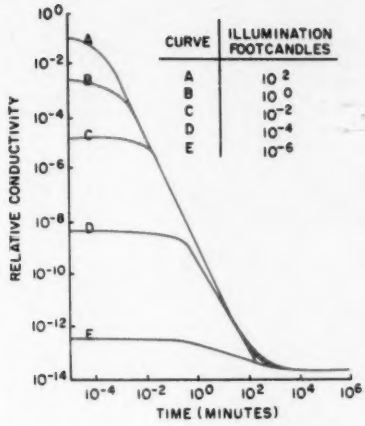


Figure 10. Delay characteristics

contribution would be made to the "on" conductivity by the deeper layers, yet their "off" conductance would reduce the "on-off" ratio. Of course, if the layer is too thin, only a small fraction of the light will be used to release carriers. For a specific material of given thickness and illumination level the conductivity per unit square of surface is a constant. This suggests that any desired conductivity can be achieved irrespective of area limitations as long as the right number of squares is provided. The most common method of achieving a high conductivity is to deposit by use of suitable masks an inter-digitalized form of electrodes as shown in Figure 13.

Whenever maximum conductance is required, the concept of cell gain becomes important. Gain is defined here as the ratio of the number of charge carriers passing between the electrodes to the number of charge carriers released by photon absorption. The gain may be expressed as:

$$G = \frac{t}{\theta} \quad ,$$

where t is the carrier lifetime and θ is the transit time. It must be understood that in referring to the charge carrier as though it were a single identifiable unit, we are in reality describing an average behavior of participants in a relay race.

In order to understand how the gain may be related to the geometry, the transit time is expressed as:

$$\theta = \frac{L^2}{\mu V} \quad ,$$

where L is the separation between electrodes, μ is the mobility of the carrier, and V is the applied voltage. If μ is considered to be a constant, then a reduction in L or an increase in V will reduce the transit time. Substitution of the value of θ into the expression for the gain yields:

$$G = \frac{t\mu V}{L^2} \quad .$$

Hence the spacing, L, of the device geometry controls the gain, at least within the limits set by the maximum value of the ratio V/L that may be used before field or avalanche effects set in. If the maximum voltage to be applied is well known, then it may be possible to achieve the desired gain with a material having a shorter carrier lifetime by reducing L to the safe minimum value. The use of a material with a shorter carrier lifetime would result in a higher speed of response, at least in the absence of trapping effects. It is often said that photoconducting materials exhibit a gain-bandwidth product; that is, as the gain is increased by increasing the carrier lifetime the response time is increased or the bandwidth decreased. This has been observed empirically, but since the decay time is more closely associated with the average time a carrier spends in a trap than with the free carrier lifetime, it may be more of a coincidence than a fundamental limitation.

When the electrode spacing has been chosen, then the "on" conductance may be determined by:

$$R^{-1} = C_1 A \Phi \quad ,$$

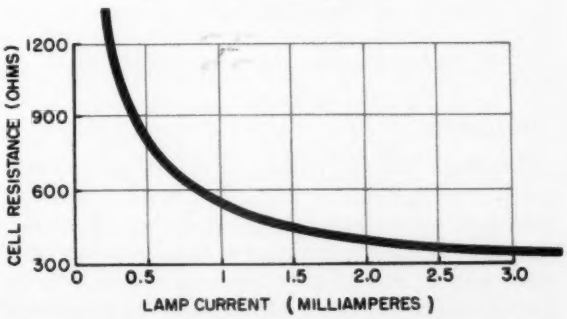


Figure 11. Cell resistance as a function of lamp current

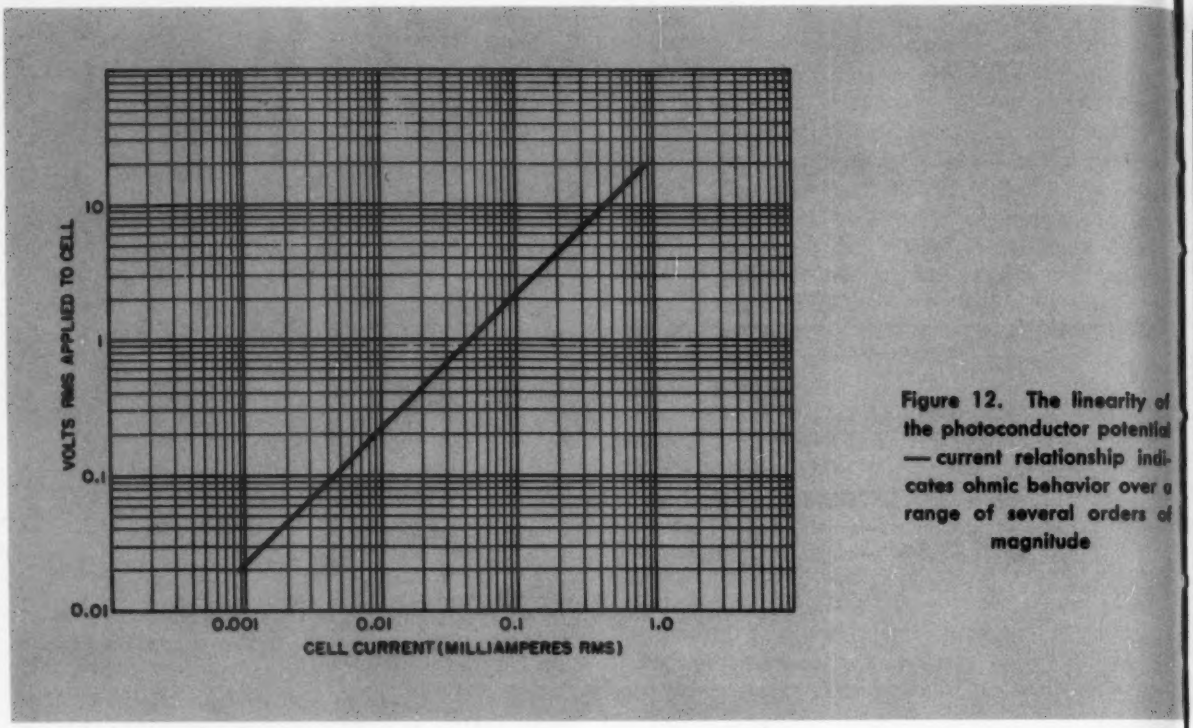


Figure 12. The linearity of the photoconductor potential — current relationship indicates ohmic behavior over a range of several orders of magnitude

where R^{-1} is the "on" conductance, C_1 is a constant, A is the cell area, and Φ is the luminous flux density. If all the light produced by the lamp is concentrated on the cell (a somewhat idealized situation), then the power input to the cell produces a luminous flux density over the cell area given by:

$$W = C_2 A \Phi \quad ,$$

where A and Φ have the same numerical values as in the previous formula. Hence, the required power, W, is related to the desired conductance by the ratio of two constants. As long as the product remains constant, A and Φ may be juggled freely. Reducing A and increasing Φ results in a better "on-off" ratio, but increasing A and reducing Φ improves the power dissipating ability. Extrapolation from present lamps and cells indicates that a photoconducting switch having only a few milliohms of contact or "on" resistance, occupying less than one cubic inch, and controlling several hundred watts is within the present state of the art.

Summary

Lamp-actuated photoconducting cells such as Raytheon's RAYSISTOR offer the circuit engineer a means of controlling AC or DC currents through a variation of purely ohmic resistance. The control is accomplished with complete galvanic or ionic isolation, and shielding of the cell from the fields induced by changing currents in the lamp is simple and effective. Some characteristics may be tailored by simple changes in cell geometry. As with most semiconductors, the effects of temperature should always be considered. The most serious limitation is the moderate speed of response, although even this is an advantage in some switching circuits where it is desirable to avoid transient over-shoot. Solid-state theory provides some insight into the cell behavior and may suggest methods of attack in cell improvement, but actual cells are a potpourri made under cook book conditions. Research on materials and techniques, directed toward improving the speed of response, is needed to develop the ultimate potential of these devices.

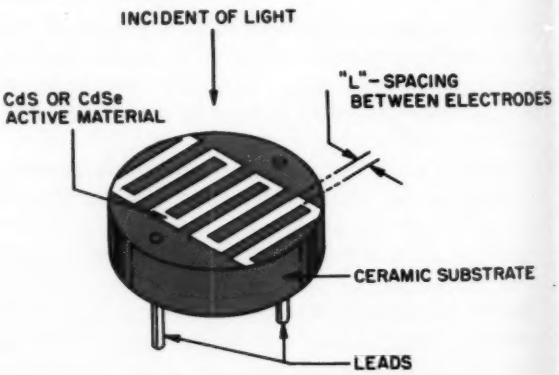


Figure 13. Typical photoconducting cell with interdigitalized electrode structure

W. A. JANOS, "On Estimating the Solution to a Class of Multipath Problems," presented at the Joint Meeting of the URSI-IRE, Boulder Laboratories, Boulder, Colo., December 12-14, 1960.

The multipath problem may be considered as one in estimating the solution to a class of differential equations with random coefficients. The randomness in the dispersive effects of the transmitting medium is expressed in the coefficients which are assumed multivariate Gaussian. If in the differential equation these coefficients are replaced by a set of deterministic ones, the solution to the consequent equation expresses an estimate of the true stochastic solution. An integral equation is derivable for the error between this estimate and true solution. On the basis of bounding the deterministic coefficients, which serve as estimating parameters, in a functional sense, an upper bound on the rms error is then derivable. It is shown that these bounds are dependent only on the singular solution (Green's function) of the deterministic problem and the correlation functions of the random coefficients. It is further shown that the rms error bound is minimized if the deterministic coefficients are the means of the random ones.

J. F. PERKINS, JR., "Improved AGC Performance for Transistor IF Amplifiers Using a Cascode Configuration," presented at the AIEE Winter General Meeting, New York, N.Y., January 29-February 3, 1961.

The advantages of the cascode type circuit configuration for transistor IF amplifiers having a wide range of AGC are presented. A study of the causes of center frequency shift and changes in Q of the IF amplifier stage is made. The variations in circuit parameters with bias conditions are investigated, and their effects upon the overall circuit performance are evaluated. The advantages of the cascode type circuit configuration are developed, and a suggested circuit is presented.

A 10 Mc/sec IF amplifier stage using the suggested cascode configuration is constructed, and test results are presented.. The work is expanded and a complete 10 Mc IF amplifier having 91 db of gain with 40 db of AGC and a bandwidth of 1.25 Mc is constructed. Test results are shown which indicate a change in bandwidth of less than 4 per cent over a 40 db range of AGC with no apparent shift in center frequency indicated.

The tuning on the experimental IF amplifier was changed to 30 Mc/sec center frequency with similar results over the AGC range.

The noise figure of the IF amplifier is given (working into an optimum source impedance) and the effect of the AGC action upon the IF amplifier noise figure is presented. The schematic diagram of the complete IF amplifier is shown, along with the test results obtained, and an effort is made to show the effectiveness and versatility of the cascode circuit configuration.

S. P. WOLSKY, E. J. ZDANUK, "Sputtering of Silicon with A^{+2} Ions," published in the Physical Review, Vol. 121, No. 2, 374-375, January 15, 1961.

A gravimetric technique involving a sensitive quartz microbalance was used for the determination of sputtering yields for the argon ion-bombardment of silicon. The sputtering yield for A^{+2} ions was deduced from the results of experiments in which the relative concentrations of A^{+} and A^{+2} ions were varied in a known manner. On the assumption that sputtering is a kinetic-energy-controlled phenomenon, we would expect $S_E(A^{+2}) = S_{2E}(A^{+})$, where S is the number of atoms sputtered by an impinging ion of energy E. This investigation showed, however, that $S_E(A^{+2}) \simeq 4S_{2E}(A^{+})$. This indicates the influence in the sputtering process of some other factor in addition to the ion kinetic energy.

G. H. ALLEN, "Reliability Requirements for B-58 Bombing-Navigation Subsystem," presented at the IRE 1961 Winter Convention on Military Electronics, Los Angeles, Calif., February 1-3, 1961.

Two subsystems for the overall B-58 Bombing-Navigation System have been designed and manufactured by Raytheon. The B-58 Bombing-Navigation System is a Doppler-stellar-inertial system which provides highly accurate guidance of B-58 supersonic aircraft to targets and automatic bombing capability. This system contains many redundant and alternate modes in order to achieve high probability of successful mission completion.

Each of the Raytheon subsystems is a basic series configuration whose reliability can be computed from the standard product rule expression. Quantitative reliability requirements which have been developed for each configuration contain the following conditions:

a) the requirements are for the total configuration. No numbers are expressed for major units within the configuration.

b) the requirements express the probability of success from B-58 take-off or wheels-up to bomb release.

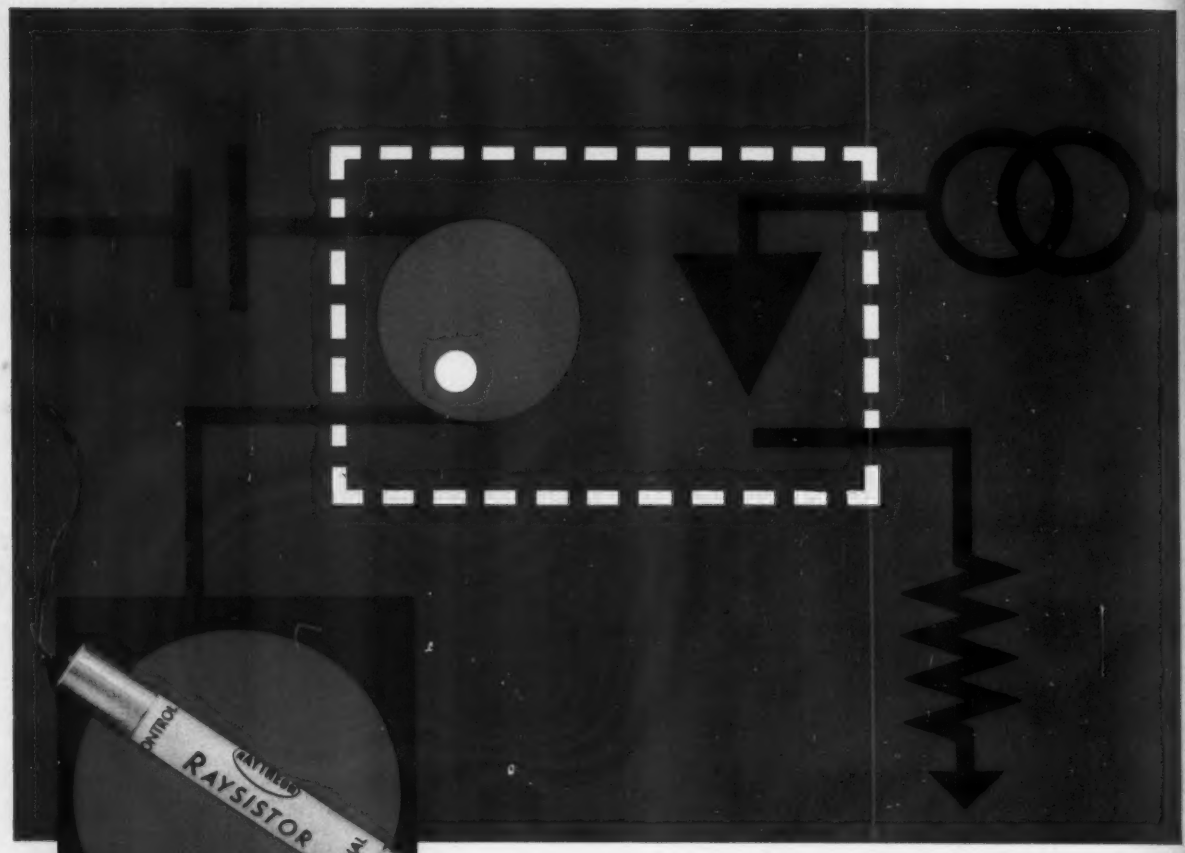
c) the requirements apply to a physical ensemble of like configuration.

d) the requirements are random survival probabilities.

e) the requirements consider failure effects by stating a probability within specification operation and a probability of no lethal failure.

f) the requirements express the capability of the configuration as delivered to the customer.

The statistical and engineering considerations which result from these general conditions are considered in this paper.



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For technical information, please write to: Raytheon, Industrial Components Division, 55 Chapel St., Newton 58, Mass.

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